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Description

Honeycomb Catalyst, Denitration Catalyst of Denitration  
Device, and Exhaust Gas Denitration Device

Technical Field

The present invention relates to a honeycomb-form catalyst (hereinafter referred to simply as honeycomb catalyst) for use in treatment of automobile exhaust gas, purification of gas, chemical synthesis, etc. More particularly, the invention relates to a high-performance NO<sub>x</sub> removal catalyst and a flue gas NO<sub>x</sub> removal apparatus, for efficiently removing NO<sub>x</sub> from flue gas produced by a facility such as a thermal power station.

Background art

Conventionally, boilers provided in thermal power stations and a variety of large-scale boilers employing a fuel such as petroleum, coal, or fuel gas, waste incinerators, and similar apparatuses have been equipped with a flue gas NO<sub>x</sub> removal apparatus for treating exhaust gas which apparatus contains a plurality of NO<sub>x</sub> removal catalyst layers.

The NO<sub>x</sub> removal catalyst is generally composed of a carrier (e.g., TiO<sub>2</sub>), an active component (e.g., V<sub>2</sub>O<sub>5</sub>), and a co-catalyst component (e.g., tungsten oxide or molybdenum oxide), and multi-component oxide NO<sub>x</sub> removal catalysts such as VO<sub>x</sub>-WO<sub>y</sub>-TiO<sub>2</sub> and VO<sub>x</sub>-MoO<sub>y</sub>-TiO<sub>2</sub> are employed.

The NO<sub>x</sub> removal catalysts typically assume the form of honeycomb, plate, etc. Honeycomb catalysts include a coated catalyst, which is fabricated by producing a honeycomb substrate and coating the substrate with a catalyst component; a kneaded catalyst, which is fabricated by kneading a substrate material with a catalyst component and molding into a honeycomb catalyst; and an impregnated catalyst, which is fabricated by impregnating a honeycomb substrate with a catalyst component. Plate-form catalyst are fabricated by coating a metallic substrate or a ceramic substrate with a catalyst component.

In any case, during use, the catalytic performance of the above catalysts is problematically deteriorated with elapse of time as a result of deposition, on the surface of the catalysts, of a substance which deteriorates the catalytic performance (hereinafter referred to as deteriorating substance) or through migration of the dissolved deteriorating substance into the catalysts.

In this connection, a variety of methods for regenerating an NO<sub>x</sub> removal catalyst has conventionally been studied.

For example, there have been studied some methods including physically removing a deteriorated portion and foreign matter so as to expose a catalytically active surface; e.g., a method including abrasion of an inner surface of a discharge gas conduit by use of an abrasive (see, for example, Patent Document 1); a method including scraping

a deteriorated surface portion of an NO<sub>x</sub> removal catalyst to thereby expose a catalytically active new surface (see, for example, Patent Document 2); and a method including causing a gas accompanying microparticles to flow through a through-hole to thereby remove foreign matter (see, for example, Patent Document 3).

In addition, there have been studied catalytic performance regeneration methods through washing; e.g., a method including washing a deteriorated catalyst with an acid (pH≤5) or an alkali (pH≥8) (see, for example, Patent Document 4); a method including washing a deteriorated catalyst sequentially with water or a dilute aqueous inorganic acid solution, with a 0.1 to 5 wt.% aqueous oxalic acid solution, and with water to remove oxalic acid residing on the catalyst (see, for example, Patent Document 5); and a method including washing a deteriorated catalyst with water (50°C to 80°C), followed by drying (see, for example, Patent Document 6).

As described above, a variety of regeneration methods have been studied. However, regarding NO<sub>x</sub> removal catalysts *per se*, the performance and specifications thereof remain unchanged.

[Patent Document 1]

Japanese Patent Application Laid-Open (*kokai*) No. 1-119343 Claims and other sections)

[Patent Document 2]

Japanese Patent Application Laid-Open (*kokai*) No. 4-197451

[Patent Document 3]

Japanese Patent Application Laid-Open (*kokai*) No. 7-116523

[Patent Document 4]

Japanese Patent Application Laid-Open (*kokai*) No. 64-80444

[Patent Document 5]

Japanese Patent Application Laid-Open (*kokai*) No. 7-222924

[Patent Document 6]

Japanese Patent Application Laid-Open (*kokai*) No. 8-196920

#### Disclosure of the Invention

In view of the foregoing, an object of the present invention is to provide a honeycomb catalyst which facilitates detection of actually deteriorated NO<sub>x</sub> removal catalysts, thereby attaining effective utilization of NO<sub>x</sub> removal catalysts. Another object of the invention is to provide an NO<sub>x</sub> removal catalyst for use in an NO<sub>x</sub> removal apparatus of the honeycomb catalyst. Still another object of the invention is to provide a flue gas NO<sub>x</sub> removal apparatus.

Accordingly, a first mode of the present invention for attaining the aforementioned objects provides a honeycomb catalyst having gas conduits for feeding a gas to be treated from an inlet to an outlet of each conduit and performing gas treatment on the sidewalls of the conduit, characterized in

that the honeycomb catalyst has an approximate length such that the flow of the gas to be treated which has been fed into the gas conduits is regulated and straightened in the vicinity of the outlet.

According to the first mode, an exhaust gas fed through the inlet of the honeycomb catalyst via the gas conduits is effectively caused to be in contact with the sidewalls until the flow of the gas is straightened, whereby catalytic reaction can be performed effectively. Thus, the honeycomb catalyst is capable of performing catalytic reaction from the inlet to a portion in the vicinity of the outlet.

A second mode of the present invention is drawn to a specific embodiment of the honeycomb catalyst of the first mode, wherein the length  $L_b$  (mm) is represented by equation (A):

$$L_b = a (L_y / L_{ys} \cdot 22e^{0.035 (L_y \cdot U_{in})}) \quad (A)$$

(wherein  $U_{in}$  (m/s) represents a gas inflow rate,  $L_y$  (mm) represents an aperture size,  $L_{ys}$  is an aperture size of 6 mm (constant value), and "a" is a constant falling within a range of 3 to 6, when the aperture size ( $L_y$ ) is 6 mm and the gas inflow rate is 6 m/s).

According to the second mode, the optimum length of the  $NO_x$  removal catalyst so as to cause the catalyst to be involved in  $NO_x$  removal reaction throughout the length thereof can be reliably and precisely specified.

A third mode of the present invention provides an  $NO_x$  removal catalyst for use in an  $NO_x$  removal apparatus, which

is a honeycomb catalyst for use in a flue gas NO<sub>x</sub> removal apparatus, the catalyst having gas conduits for feeding an exhaust gas from an inlet to an outlet of each conduit and performing NO<sub>x</sub> removal on the sidewalls of the conduit, characterized in that the NO<sub>x</sub> removal catalyst has an approximate length such that the flow of the exhaust gas which has been fed into the gas conduits is straightened in the vicinity of the outlet.

According to the third mode, an exhaust gas fed through the inlet of the NO<sub>x</sub> removal catalyst via the gas conduits is effectively caused to be in contact with the sidewalls until the flow of the gas is straightened, whereby NO<sub>x</sub> removal reaction can be performed effectively. Thus, the NO<sub>x</sub> removal catalyst is capable of performing catalytic reaction from the inlet to a portion in the vicinity of the outlet.

A fourth mode of the present invention is drawn to a specific embodiment of the NO<sub>x</sub> removal catalyst of the third mode for use in an NO<sub>x</sub> removal apparatus; wherein the length L<sub>b</sub> (mm) is represented by equation (A):

$$L_b = a(L_y/L_{ys} \cdot 22e^{0.035(L_y \cdot U_{in})}) \quad (A)$$

(wherein U<sub>in</sub> (m/s) represents a gas inflow rate, L<sub>y</sub> (mm) represents an aperture size, L<sub>ys</sub> is an aperture size of 6 mm (constant value), and "a" is a constant falling within a range of 3 to 6, when the aperture size (L<sub>y</sub>) is 6 mm and the gas inflow rate is 6 m/s).

According to the fourth mode, the optimum length of the NO<sub>x</sub> removal catalyst so as to cause the catalyst to be

involved in NO<sub>x</sub> removal reaction throughout the length thereof can be reliably and precisely specified.

A fifth mode of the present invention is drawn to a specific embodiment of the NO<sub>x</sub> removal catalyst of the third mode for use in an NO<sub>x</sub> removal apparatus, wherein the length of the NO<sub>x</sub> removal catalyst falls within a range of 300 mm to 450 mm.

According to the fifth mode, the catalyst is involved in NO<sub>x</sub> removal reaction throughout the entire length thereof.

A sixth mode of the present invention provides a flue gas NO<sub>x</sub> removal apparatus comprising a plurality of NO<sub>x</sub> removal catalyst layers provided in the gas flow direction, each catalyst layer being composed of a plurality of honeycomb NO<sub>x</sub> removal catalysts juxtaposed in a direction crossing the gas flow direction,

each honeycomb NO<sub>x</sub> removal catalyst having gas conduits for feeding an exhaust gas from an inlet to an outlet of each conduit and performing NO<sub>x</sub> removal on the sidewalls of the conduit,

characterized in that each of the NO<sub>x</sub> removal catalysts forming each NO<sub>x</sub> removal catalyst layer has an approximate length such that the flow of the exhaust gas which has been fed into the gas conduits is straightened in the vicinity of the outlet, and two NO<sub>x</sub> removal catalyst layers adjacent to each other are disposed with a space therebetween, the space serving as a common gas conduit where exhaust gas flows discharged through the NO<sub>x</sub> removal catalysts are intermingled

one another.

According to the sixth mode, the flow of an exhaust gas fed through the inlets of the NO<sub>x</sub> removal catalyst layers via the gas conduits is not straightened to a portion in the vicinity of the outlet and is effectively caused to be in contact with the sidewalls, whereby NO<sub>x</sub> removal reaction can be performed effectively. The exhaust gas flow discharged through each NO<sub>x</sub> removal catalyst layer forms turbulent flow in each common gas conduit, and the turbulent flow is introduced to a subsequent NO<sub>x</sub> removal catalyst layer. Thus, the entirety of the subsequent NO<sub>x</sub> removal catalyst can also be effectively involved in NO<sub>x</sub> removal reaction.

A seventh mode of the present invention is drawn to a specific embodiment of the flue gas NO<sub>x</sub> removal apparatus of the sixth mode, wherein the length L<sub>b</sub> (mm) is represented by equation (A):

$$L_b = a(L_y/L_{ys} \cdot 22e^{0.035(L_y \cdot U_{in})}) \quad (A)$$

(wherein U<sub>in</sub> (m/s) represents a gas inflow rate, L<sub>y</sub> (mm) represents an aperture size, L<sub>ys</sub> is an aperture size of 6 mm (constant value), and "a" is a constant falling within a range of 3 to 6, when the aperture size (L<sub>y</sub>) is 6 mm and the gas inflow rate is 6 m/s).

According to the seventh mode, the optimum length of the NO<sub>x</sub> removal catalyst so as to cause the catalyst to be involved in NO<sub>x</sub> removal reaction throughout the length thereof can be reliably and precisely specified.

An eighth mode of the present invention is drawn to a



specific embodiment of the flue gas NO<sub>x</sub> removal apparatus of the sixth mode, wherein the length of the NO<sub>x</sub> removal catalyst falls within a range of 300 mm to 450 mm.

According to the eighth mode, the catalyst is involved in NO<sub>x</sub> removal reaction throughout the entire length thereof.

A ninth mode of the present invention is drawn to a specific embodiment of the flue gas NO<sub>x</sub> removal apparatus of the seventh or eighth mode, which has 3 to 5 stages of the NO<sub>x</sub> removal catalyst layers having a specific length (Lb).

According to the ninth mode, all of the provided NO<sub>x</sub> removal catalyst layers are effectively involved in NO<sub>x</sub> removal reaction.

The present invention is applicable to any type of conventionally employed honeycomb catalyst. The term "honeycomb catalyst" refers to a catalyst unit including gas conduits having a cross-section of a polygon such as square, hexagon, or triangle, and performing catalytic reaction on the sidewalls of the gas conduits. No particular limitation is imposed on the form of the honeycomb catalyst, and typical forms include a cylinder containing gas conduits each having a hexagonal cross-section, and a rectangular prism containing gas conduits each having a square cross-section and arranged in a lattice-like form.

Conventionally, typical honeycomb NO<sub>x</sub> removal catalysts have a gas conduit pitch of 7 mm (aperture size: about 6 mm) and a length of about 700 mm to 1,000 mm. The present inventors have investigated the deterioration status of such

catalysts after use along a longitudinal direction, and have found that the catalysts are more deteriorated on the inlet side than on the outlet side; the deterioration status is virtually unchanged in a portion ranging from the 300 mm site from the inlet to the outlet; and particularly, the catalysts are less involved in  $\text{NO}_x$  removal reaction in a portion ranging from the outlet to the 300 mm site (from the outlet) than in a portion on the inlet side. The present invention has been accomplished on the basis of these findings. In other words, the present invention has been accomplished on the basis of the following finding by the inventors. Specifically, an exhaust gas is fed into an  $\text{NO}_x$  removal catalyst through gas conduits as a turbulent flow, and  $\text{NO}_x$  removal reaction is performed through contact of the gas with the sidewalls of the gas conduits. However, the flow of the thus-reacted exhaust gas is gradually straightened. Contact of the straightened gas flows with the sidewalls of the conduits is minimized, thereby failing to attain effective  $\text{NO}_x$  removal.

Furthermore, one conceivable mechanism that explains reduction in  $\text{NO}_x$ - or  $\text{NH}_3$ -removal efficiency is as follows. When an exhaust gas is fed from a wide space on the upstream side of the  $\text{NO}_x$  removal catalyst to gas conduits of the catalyst, percent space of the gas is reduced from 1 to 0.6 to 0.7. The exhaust gas passes through the gas conduits while being in contact with the sidewalls of the conduits (catalyst surfaces) in a considerably turbulent state.

However, during the course of passage through the conduits, the gas flows are gradually regulated and straightened and mass transfer is controlled through diffusion only. After straightening,  $\text{NO}_x$  molecules and  $\text{NH}_3$  molecules which are to collide with the sidewalls decrease in number considerably.

Thus, when an  $\text{NO}_x$  removal catalyst including gas conduits each having an aperture size of 6 mm (pitch: about 7 mm) is used, the flow of introduced exhaust gas is straightened at a depth of about 300 to 450 mm from the inlet, although the depth varies depending on the flow conditions of the exhaust gas. According to the present invention,  $\text{NO}_x$  removal catalysts each having a length of about 300 to 450 mm are incorporated into a flue gas  $\text{NO}_x$  removal apparatus. The length is suitable for attaining effective utilization of the  $\text{NO}_x$  catalysts, and  $\text{NO}_x$  removal performance is unchanged, even though the length of the catalysts increases. As compared with conventional, typical cases in which two stages of  $\text{NO}_x$  removal catalysts each having a length of 700 mm to 1,000 mm are employed, use of three stages of  $\text{NO}_x$  removal catalysts each having a length of 400 mm to 500 mm or use of four or more stages of  $\text{NO}_x$  removal catalysts each having a length of about 300 mm remarkably enhances  $\text{NO}_x$  removal performance. Preferably, two  $\text{NO}_x$  removal catalyst layers adjacent to each other are disposed with a space therebetween, the space serving as a common gas conduit where exhaust gas flows that are to be treated and that are discharged through the  $\text{NO}_x$  removal catalysts are intermingled one another. The length

of the common gas conduit is preferably such that turbulent flow is satisfactorily formed. Needless to say, a baffle plate or a similar member for intentionally forming turbulent flow may be provided in the common gas conduit.

Meanwhile,  $\text{NO}_x$  removal by use of an  $\text{NO}_x$  removal catalyst is performed at an exhaust gas flow rate of about 5 m/sec to 10 m/sec, and a honeycomb catalyst is considered to provide the same  $\text{NO}_x$  removal effect when used under such a flow rate.

In the honeycomb catalyst of the present invention, catalytic reaction occurs on the sidewalls of the honeycomb structure. Thus, the honeycomb catalyst may be employed not only as an  $\text{NO}_x$  removal catalyst for use in a flue gas  $\text{NO}_x$  removal apparatus, but also as a type of catalyst for any purpose, so long as the catalyst has structural characteristics such that fluid to be treated passes through the honeycomb. In particular, the honeycomb catalyst is applicable to any case where the fluid to be reacted contains a substance that deteriorates the catalyst to reduce reaction efficiency.

As described hereinabove, the present invention provides a honeycomb catalyst and an  $\text{NO}_x$  removal catalyst for use in an  $\text{NO}_x$  removal apparatus which can be employed at high efficiency, and a flue gas  $\text{NO}_x$  removal apparatus, whereby the running cost of a flue gas  $\text{NO}_x$  removal system in terms of the  $\text{NO}_x$  removal catalyst is reduced by about one-half.

Brief Description of the Drawings

FIG. 1 schematically shows a configuration of a flue gas NO<sub>x</sub> removal apparatus employing an NO<sub>x</sub> removal catalyst management unit according to one embodiment of the present invention.

FIG. 2 is a graph showing the results of Test Example 1 of the present invention.

FIG. 3 is a graph showing the results of Test Example 2 of the present invention.

FIG. 4 is a graph showing the results of Test Example 2 the present invention.

FIG. 5 is a graph showing the results of Test Example 3 the present invention.

FIG. 6 is a graph showing the results of Test Example 4 the present invention.

FIG. 7 is a graph showing the results of Test Example 4 the present invention.

FIG. 8 is a graph showing the results of Test Example 5 the present invention.

FIG. 9 is a graph showing the results of Test Example 6 the present invention.

#### Best Modes for Carrying Out the Invention

Best modes for carrying out the invention will next be described with reference to the FIGs. The description is made only for the illustration purpose, and should not be construed as limiting the invention thereto. The present embodiment is the case in which a honeycomb catalyst is

employed as an NO<sub>x</sub> removal catalyst used in a flue gas NO<sub>x</sub> removal apparatus. Needless to say, the present invention is not limited to such use.

<Embodiment>

FIG. 1 schematically shows a configuration of a flue gas NO<sub>x</sub> removal apparatus equipped with an NO<sub>x</sub> removal catalyst according to one embodiment of the present invention. Actually, the flue gas NO<sub>x</sub> removal apparatus is provided in a thermal power station. However, no particular limitation is imposed on the facility that includes the NO<sub>x</sub> removal catalyst management unit of the embodiment.

As shown in FIG. 1, a flue gas NO<sub>x</sub> removal apparatus 10 includes an exhaust duct 12 and a treated gas duct 13. The exhaust duct 12 is in communication with a boiler unit installed in a thermal power station that is connected with an apparatus body 11 on the upstream side. The treated gas duct 13 is connected with the apparatus body 11 on the downstream side. In the apparatus body 11, a plurality of NO<sub>x</sub> removal catalyst layers (4 layers in this embodiment) 14A to 14D are disposed at predetermined intervals. The NO<sub>x</sub> removal catalyst layers 14A to 14D are arranged so that a discharge gas introduced through the exhaust duct 12 is sequentially passed therethrough, and reduce the level of nitrogen oxide (NO<sub>x</sub>) of the discharge gas through contact with the discharge gas passing through the catalyst layers. Notably, to the exhaust duct 12 communicating with the boiler unit, NH<sub>3</sub> is injected in an amount in accordance with the

amount of the discharge gas fed from the boiler body.

No particular limitation is imposed on the type, shape, etc. of the NO<sub>x</sub> removal catalysts 14 forming the NO<sub>x</sub> removal catalyst layers 14A to 14D. Generally, each catalyst is composed of TiO<sub>2</sub> serving as a carrier and V<sub>2</sub>O<sub>5</sub> serving as an active component. In this embodiment, honeycomb catalysts were employed. In the present embodiment, each catalyst layer employs a catalyst in the form of columnar honeycomb, and a plurality of honeycomb catalysts are juxtaposed in combination, thereby forming the catalyst layers 14A to 14D. Each NO<sub>x</sub> removal catalyst 14 has a length of 350 mm and includes a plurality of gas conduits 14a arranged at pitches of 7 mm. The interlayer spacing between two adjacent NO<sub>x</sub> removal catalyst layers 14A to 14D is about 2,000 mm, which corresponds to the height for allowing a person to perform inspection or sampling of a catalyst. Each interlayer space serves as a common gas conduit 19.

An NO<sub>x</sub> removal catalyst management unit 20 is provided with gas sampling means 15A through 15E on the inlet and outlet sides of respective NO<sub>x</sub> removal catalyst layers 14A through 14D. The gas sampling means 15A through 15E are connected with NO<sub>x</sub> concentration measurement means 16A through 16E and with NH<sub>3</sub> concentration measurement means 17A through 17E. The data obtained by the measurement means are transferred to a percent NO<sub>x</sub> removal determination means 18 for calculating percent NO<sub>x</sub> removal and percent NO<sub>x</sub> removal contribution of the respective NO<sub>x</sub> removal catalyst layers

14A through 14D.

The gas sampling means 15A through 15E sample, via sampling tubes, a gas to be sampled in a desired amount and at a desired timing, and subsequently feed the sampled gas to the NO<sub>x</sub> concentration measurement means 16A through 16E and to the NH<sub>3</sub> concentration measurement means 17A through 17E.

No particular limitation is imposed on the timing for sampling a gas by the gas sampling means 15A through 15E. Generally, sampling is carried out during usual operation of the power station, preferably at the nominal load where the amount of gas reaches the maximum, if possible. The interval between sampling operations may be prolonged to about six months, and the interval is sufficient for managing the performance of the NO<sub>x</sub> removal catalyst layers 14A through 14D. However, if the interval is shortened, precision in management is enhanced. Thus, the sampling is preferably carried out, for example, once every one to two months. Particularly, in a catalyst layer placed on the downstream side, variation of obtained data increases due to decrease in NH<sub>3</sub> concentration. Thus, in order to attain better management and evaluation, preferably, determination of NH<sub>3</sub> concentration is performed at short intervals, and percent NO<sub>x</sub> removal is calculated from an averaged NH<sub>3</sub> concentration value.

The percent NO<sub>x</sub> removal determination means 18 collects the measurement data from the NO<sub>x</sub> concentration measurement means 16A through 16E and the NH<sub>3</sub> concentration measurement



means 17A through 17E, and calculates, from the measurement data, percent NO<sub>x</sub> removal and percent NO<sub>x</sub> removal contribution of respective NO<sub>x</sub> removal catalyst layers 14A through 14D.

On the basis of an inlet mole ratio (i.e., inlet NH<sub>3</sub>/inlet NO<sub>x</sub>) of the NO<sub>x</sub> removal catalyst layers 14A through 14D, the NH<sub>3</sub>-concentration-based percent NO<sub>x</sub> removal ( $\eta$ ) is determined from the following equation (1):

$$\eta = \{(\text{inlet NH}_3 - \text{outlet NH}_3) / (\text{inlet NH}_3 - \text{outlet NH}_3 + \text{outlet NO}_x)\} \times 100 \times (\text{evaluation mole ratio} / \text{inlet mole ratio}) \quad (1).$$

As used herein, the term "evaluation mole ratio" refers to a mole ratio which is predetermined for the purpose of evaluating an NO<sub>x</sub> removal catalyst. The evaluation mole ratio may be predetermined to an arbitrary value; for example, 0.8, which is almost equal to a mole ratio typically employed for operating a power station.

#### <Comparative Example>

The procedure of Example was repeated, except that the length of each NO<sub>x</sub> removal catalyst was changed to 860 mm, to thereby provide a flue gas NO<sub>x</sub> removal apparatus.

#### <Test Example 1>

From an NO<sub>x</sub> removal catalyst layer which had been used for 50,000 hours in the apparatus of Comparative Example, catalyst portions (20 mm site to 850 mm site, from the inlet) were sampled in the longitudinal direction. TiO<sub>2</sub> concentration and concentrations of catalyst deterioration substances (CaO and SO<sub>3</sub>) on the surface of each catalyst

sample were determined.

Catalyst portions (50 mm × 50 mm × 100 mm in length) were cut from a catalyst included in each catalyst layer, and set in a performance test machine. Portions at the 100 mm site, the 450 mm site, and the 800 mm site were tested. The test gas was fed at a mole ratio (inlet mole ratio = inlet  $\text{NH}_3$ /inlet  $\text{NO}_x$ ) of 0.82 and an AV (amount of treatable gas per unit surface area of the catalyst) of 6.5, and percent  $\text{NO}_x$  removal  $\eta$  was calculated on the basis of the aforementioned formula (1) employing  $\text{NH}_3$  concentration.

The results are shown in FIG. 2. As a reference product, a new (unused) catalyst was also measured in terms of percent  $\text{NO}_x$  removal.

The results indicate that the catalyst was severely deteriorated in a portion ranging from the inlet to the 300 mm site, and that a portion ranging from the 450 mm to the outlet exhibits percent  $\text{NO}_x$  removal almost equal to that of a new catalyst product.

#### <Test Example 2>

An  $\text{NO}_x$  removal catalyst which had been used for 28,000 hours, after regeneration through washing with water, in the apparatus of Comparative Example, was re-installed in the flue gas  $\text{NO}_x$  removal apparatus such that the catalyst was inverted with respect to the direction of the flow of discharge gas. FIG. 3 shows the results.

The results indicate that the inverted catalyst exhibits  $\text{NO}_x$  removal performance approximately equal to that

of a new catalyst product.

After regeneration and use for 30,000 hours, the inverted catalyst was investigated in terms of change in percent  $\text{NO}_x$  removal. The results are shown in FIG. 4. As is clear from FIG. 4, a portion on the outlet side of the catalyst was not deteriorated and maintained performance as high as that of a new catalyst product. The portion *per se* was found to exhibit sufficient  $\text{NO}_x$  removal performance.

<Test Example 3>

The  $\text{NO}_x$  removal which had been used in the apparatus of Comparative Example was cut at the 600 mm site from the inlet (along the longitudinal direction), and the cut catalyst piece was set in a performance test machine. Percent  $\text{NO}_x$  removal was determined at a plurality of sites at intervals of 100 mm under the following conditions: mole ratios (i.e., inlet mole ratio = inlet  $\text{NH}_3$ /inlet  $\text{NO}_x$ ) of 0.6, 0.8, 1.0, and 1.2; 360°C; and fluid inflow rate of 6 m/s. The results are shown in Table 1 and FIG. 5.

The results indicate that percent  $\text{NO}_x$  removal tends to increase in proportion to the distance from the inlet (i.e., length of the catalyst) and that the increase in percent  $\text{NO}_x$  removal tends to be suppressed when the catalyst length exceeds a certain value. The tendency is attributable to the flow of exhaust gas being gradually straightened.

[Table 1]

	100	200	300	400	500	600
0.6	17.7	30.4	39.5	46.1	50.8	54.2
0.8	21.3	36.9	48.3	56.7	62.9	67.4
1.0	23.2	40.5	53.5	63.2	70.5	75.9
1.2	24.0	42.0	55.4	65.4	73.0	78.6

<Test Example 4>

A honeycomb catalyst (600 mm × 6 mm × 6 mm, aperture size: 6 mm (pitch: 7 mm)) was subjected to simulation under the following conditions: 350°C and fluid inflow rate (Uin): 4, 6, and 10 m/s.

The simulation results of the honeycomb catalyst indicate that Uin and the distance from the inlet to a site where turbulent flow energy is lost in the course of transition from turbulent flow to laminar flow (hereinafter referred to as sustained turbulent flow distance (Lts)) have the relationship shown in FIG. 6. Specifically, sustained turbulent flow distance (Lts) values at fluid inflow rates (Uin) of 4, 6, and 10 m/s were calculated as 50, 80, and 180 mm, respectively.

Theoretically, conditions of fluid are generally determined from inflow rate (Uin) and Reynolds number Re; i.e., a parameter employing aperture size Ly ( $Re = Uin \cdot Ly / v$ ,  $v = 5.67 \times 10^{-5} \text{ m}^2/\text{S}$ ; constant).

In a honeycomb catalyst having an aperture size of 6 mm, sustained turbulent flow distance Lts (mm) is derived from a product of inflow rate Uins (m/s) and aperture size Lys (mm). Thus, the relationship between sustained turbulent flow

distance  $L_{ts}$  and a product of inflow rate  $U_{in}$  ( $U_{in}$ ) and aperture size  $L_y$  ( $L_y$ ), as shown in FIG. 6, was obtained. Through the least squares method, sustained turbulent flow distance  $L_{ts}$  at an aperture size ( $L_y$ ) of 6 mm is approximately represented by the following equation (2).

$$L_{ts} = 22e^{0.035(L_y \cdot U_{in})} \quad (2)$$

When the aperture size  $L_y$  is 6 mm (constant value), the aperture size  $L_y$  (mm) is an arbitrary parameter, and  $U_{in}$  (m/s) represents a gas inflow rate, sustained turbulent flow distance  $L_t$  can be represented by the following formula (3), which is a general equation.

$$L_t = L_y/L_y \cdot 22e^{0.035(L_y \cdot U_{in})} \quad (3)$$

The simulation results were compared with the approximate length (optimum length) of the actual catalyst, the length being such that the flow of the exhaust gas fed into the gas conduits is straightened. Specifically, the relationship between sustained turbulent flow distance  $L_t$  and the optimum length of an actual catalyst (i.e., the length of a stained portion of the catalyst (stain length), which is an index for detecting straightening) was investigated. As shown in FIG. 7, in an actual stage of the employed apparatus, turbulent flow is maintained over a portion of the catalyst having a distance longer than the sustained turbulent flow

distance  $L_t$ , which is derived through simulation. One possible reason of this phenomenon is that inflow rate is varied and flow of the fluid is disturbed.

Accordingly, in an actual catalyst unit, the distance from the inlet to a site where straightening starts (i.e., the optimum catalyst length) must be determined from the above stain length and a certain safety length. Specifically, equation (3) must be multiplied by a constant " $a$ ," and the optimum length  $L_b$  of the catalyst is considered to be represented by the following equation (4). Note that " $a$ " is a constant falling within a range of 3 to 6, when the aperture size of a honeycomb catalyst is 6 mm (pitch: 7 mm) and the gas inflow rate is 6 m/s.

$$L_b = a \cdot L_t \quad (4)$$

In the aforementioned Test Example 1, a honeycomb catalyst having an aperture size of 6 mm (pitch: 7 mm) was used at a gas inflow rate of 6 m/s. Thus,  $L_t$  is 80 mm. When the constant " $a$ " is adjusted to about 3.8,  $L_t$  is about 300 mm, which corresponds to the length of a severely deteriorated portion of the catalyst, whereas when the constant " $a$ " is adjusted to about 5.6,  $L_t$  is about 450 mm, which corresponds to the length of a portion of the catalyst including a portion exhibiting catalytic performance equivalent to that of a new catalyst product.

In the same honeycomb catalyst, when " $a$ " falls within a

range of 3 to 6, the optimum length  $L_b$  falls within a range of about 240 to 480 mm. The range of  $L_b$  virtually coincides with a range of about 300 to 450 mm, which is considered to be a catalyst length which allows the exhaust gas in the gas conduits starts straightening of the flow. Thus, the optimum length  $L_b$  is selected from the range of 240 to 480 mm, corresponding to the "a" value of 3 to 6.

<Test Example 5>

The concept and equation (4) about the optimum length  $L_b$ , which were obtained in Test Example 4, was confirmed in apparatus design. Specifically, a variety of catalyst layer sets having different catalyst lengths and stage numbers were analyzed in terms of percent overall  $\text{NO}_x$  removal and unreacted  $\text{NH}_3$  through a conventional apparatus designing method on the basis of an SV value (amount of treatable gas per unit volume of the catalyst) and an AV value (amount of treatable gas per unit surface area of the catalyst). The catalyst layer sets (length and number of layers) are as follows: Pattern 1 (in Table 2); catalyst length 1,000 mm, 1 stage, Pattern 2 (in Table 2); catalyst length 500 mm, 2 stages, Pattern 3 (in Table 2); catalyst length 333 mm, 3 stages, Pattern 4 (in Table 2); catalyst length 250 mm, 4 stages, and Pattern 5 (in Table 2); catalyst length 200 mm, 5 stages. The evaluation results of the catalyst sets are shown in Table 2 and FIG. 8.

The results indicate that, even when the total catalyst length is the same, a multi-stage catalyst exhibits an

enhanced percent  $\text{NO}_x$  removal, and that a catalyst set (catalyst length 250 mm, 4 stages) exhibited the highest overall percent  $\text{NO}_x$  removal. As compared with the case of a catalyst (catalyst length 1,000 mm, 1 stage) (percent  $\text{NO}_x$  removal: 84.3%), a catalyst set (catalyst length 250 mm, 4 stages), the percent  $\text{NO}_x$  removal was as high as 90%. In this case, unreacted  $\text{NH}_3$  was minimized. As a result, when a honeycomb catalyst having an aperture size of 6 mm (pitch: 7 mm) is used at a gas inflow rate of 6 m/s, the optimum length thereof is approximately 250 mm, which falls within the optimum length  $L_b$  range of 240 mm to 480 mm, calculated by equation (4).

In addition, when three to five stages of catalyst layers having a length almost equivalent to that of the optimum length  $L_b$  are provided, high overall percent  $\text{NO}_x$  removal was found to be attained.



[Table 2]

Pattern		1	2	3	4	5
SV ( $\text{m}_3\text{N}/\text{h}\cdot\text{m}^3$ )		5,950	5,950	5,950	5,950	5,950
AV ( $\text{m}_3\text{N}/\text{h}\cdot\text{m}^2$ )		14.9	14.9	14.9	14.9	14.9
Catalyst length (mm)		1,000	500	333	250	200
Inlet $\text{NO}_x$ (ppm)		300	300	300	300	300
Inflow mole ratio		0.95	0.95	0.95	0.95	0.95
Inlet $\text{NH}_3$ (ppm)		285	285	285	285	285
Stage 1	$\text{NO}_x$ removal (%)	84.3	68.6	56.0	46.9	39.6
	Outlet $\text{NO}_x$ (ppm)	47	94	132	159	181
	Outlet $\text{NH}_3$ (ppm)	32	79	117	144	166
	Mole ratio	0.68	0.84	0.89	0.91	0.92
Stage 2	$\text{NO}_x$ removal (%)		64.4	54.2	45.9	39.0
	Outlet $\text{NO}_x$ (ppm)		34	61	86	110
	Outlet $\text{NH}_3$ (ppm)		19	46	71	95
	Mole ratio			0.75	0.83	0.86
Stage 3	$\text{NO}_x$ removal (%)			49.5	44.1	38.1
	Outlet $\text{NO}_x$ (ppm)			31	48	68
	Outlet $\text{NH}_3$ (ppm)			16	33	53
	Mole ratio				0.69	0.78
Stage 4	$\text{NO}_x$ removal (%)				39.2	36.3
	Outlet $\text{NO}_x$ (ppm)				29	44
	Outlet $\text{NH}_3$ (ppm)				14	29
	Mole ratio					0.66
Stage 5	$\text{NO}_x$ removal (%)					32.2
	Outlet $\text{NO}_x$ (ppm)					30
	Outlet $\text{NH}_3$ (ppm)					15
Apparatus outlet $\text{NO}_x$ (ppm)		47.1	33.5	30.6	29.2	29.6
Overall $\text{NO}_x$ removal (%)		84.3	88.8	89.8	90.3	90.1
Unreacted $\text{NH}_3$ (ppm)		32	19	16	14	15

## &lt;Test Example 6&gt;

In a manner similar to Test Example 5, the catalyst layer sets (length and type of catalyst layer(s)) shown in Test Example 5 were analyzed in terms of apparatus outlet  $\text{NO}_x$  and unreacted  $\text{NH}_3$  through a conventional apparatus designing method under the conditions: inlet  $\text{NO}_x$  = 1,000 ppm, inflow mole ratio = 0.83, and inlet  $\text{NH}_3$  = 830 ppm). The results are shown in Table 3 and FIG. 9.

The results indicate that a catalyst set (catalyst length 250 mm, 4 stages) exhibited the lowest apparatus outlet NO<sub>x</sub> and unreacted NH<sub>3</sub>. Therefore, a honeycomb catalyst having a length of 250 mm was found to effectively work in an apparatus where high concentration NO<sub>x</sub> must be treated (e.g., NO<sub>x</sub> removal apparatus for a diesel engine).

[Table 3]

Pattern		1	2	3	4	5
SV (m <sub>3</sub> N/h·m <sup>3</sup> )		5,950	5,950	5,950	5,950	5,950
AV (m <sub>3</sub> N/h·m <sup>2</sup> )		14.9	14.9	14.9	14.9	14.9
Catalyst length (mm)		1,000	500	333	250	200
Inlet NO <sub>x</sub> (ppm)		1,000	1,000	1,000	1,000	1,000
Inflow mole ratio		0.83	0.83	0.83	0.83	0.83
Inlet NH <sub>3</sub> (ppm)		830	830	830	830	830
Stage 1	NO <sub>x</sub> removal (%)	77.9	64.0	52.6	44.2	37.4
	Outlet NO <sub>x</sub> (ppm)	221	360	474	558	626
	Outlet NH <sub>3</sub> (ppm)	51	190	304	388	456
	Mole ratio	0.23	0.53	0.64	0.70	0.73
Stage 2	NO <sub>x</sub> removal (%)		44.7	44.2	39.5	34.6
	Outlet NO <sub>x</sub> (ppm)		199	265	337	409
	Outlet NH <sub>3</sub> (ppm)		29	95	167	239
	Mole ratio			0.36	0.50	0.58
Stage 3	NO <sub>x</sub> removal (%)			25.2	29.6	29.6
	Outlet NO <sub>x</sub> (ppm)			198	238	288
	Outlet NH <sub>3</sub> (ppm)			28	68	118
	Mole ratio				0.28	0.41
Stage 4	NO <sub>x</sub> removal (%)				17.0	20.8
	Outlet NO <sub>x</sub> (ppm)				197	228
	Outlet NH <sub>3</sub> (ppm)				27	58
	Mole ratio					0.26
Stage 5	NO <sub>x</sub> removal (%)					12.9
	Outlet NO <sub>x</sub> (ppm)					199
	Outlet NH <sub>3</sub> (ppm)					29
Apparatus outlet NO <sub>x</sub> (ppm)		221.5	199.0	198.0	197.3	198.8
Overall NO <sub>x</sub> removal (%)		77.9	80.1	80.2	80.3	80.1
Unreacted NH <sub>3</sub> (ppm)		51	29	28	27	29

<Test Example 7>

Two types of NO<sub>x</sub> removal catalyst sets for a diesel

engine were provided for removal of high concentration  $\text{NO}_x$ . In one catalyst set, the first stage was divided to form a multi-stage, and no such division is performed with respect to the other catalyst set. In a manner similar to Test Example 5, apparatus outlet  $\text{NO}_x$ , overall percent  $\text{NO}_x$  removal, and unreacted  $\text{NH}_3$  were calculated through a conventional apparatus designing method. The results are shown in Table 4.

As is clear from Table 4, as compared with the case in which the first stage remained undivided, the divided first stage (700 mm into 350 mm + 350 mm), each divided stage having an optimum  $L_b$ , exhibited a slightly reduced apparatus outlet  $\text{NO}_x$  and unreacted  $\text{NH}_3$  and a slightly enhanced overall percent  $\text{NO}_x$  removal. In other words, when a catalyst having a length that is about double the optimum length  $L_b$  the aforementioned equation (4) is divided, all catalytic performances including apparatus outlet  $\text{NO}_x$ , overall percent  $\text{NO}_x$  removal, and unreacted  $\text{NH}_3$  can be enhanced.

Therefore, in an apparatus employing an  $\text{NO}_x$  removal catalyst having a length twice or more the optimum length  $L_b$ , when the  $\text{NO}_x$  removal catalyst is divided into sub-layers having an approximate optimum length  $L_b$ , performance of the apparatus is considered to be enhanced. In Test Example 7, if the stage 2 catalyst layer and the stage 3 catalyst layer (shown in Table 4), each having a length of 700 mm, are divided into sub-layers having an approximate optimum length  $L_b$ , performance of the apparatus is considered to be surely enhanced.

[Table 4]

		Non- divided stage	Divided- stages
SV ( $\text{m}_3\text{N/h}\cdot\text{m}^3$ )		5,950	5,950
AV ( $\text{m}_3\text{N/h}\cdot\text{m}^2$ )		14.9	14.9
Catalyst length/ stage 1 (mm)		700	350
Catalyst length/ stage 1 divided (mm)			350
Catalyst length/ stage 2 (mm)		700	700
Catalyst length/ stage 3 (mm)			
Catalyst Stage		2	3
Inlet NO <sub>x</sub> (ppm)		1,000	1,000
Inflow mole ratio		0.81	0.81
Inlet NH <sub>3</sub> (ppm)		810	810
Stage 1	NO <sub>x</sub> removal (%)	71.2	53.5
	Outlet NO <sub>x</sub> (ppm)	288	465
	Outlet NH <sub>3</sub> (ppm)	98	275
	Mole ratio	0.34	0.59
Stage 2	NO <sub>x</sub> removal (%)	32.2	42.8
	Outlet NO <sub>x</sub> (ppm)	195	266
	Outlet NH <sub>3</sub> (ppm)	5	76
	Mole ratio		0.29
Stage 3	NO <sub>x</sub> removal (%)		27.0
	Outlet NO <sub>x</sub> (ppm)		194
	Outlet NH <sub>3</sub> (ppm)		4
	Mole ratio		
Apparatus outlet NO <sub>x</sub> (ppm)		195.5	194.2
Overall NO <sub>x</sub> removal (%)		80.5	80.6
Unreacted NH <sub>3</sub> (ppm)		5	4

### Industrial Applicability

The present invention is remarkably advantageous for a catalyst and an apparatus which are required to perform high-level  $\text{NO}_x$  removal and high-concentration  $\text{NO}_x$  removal treatment.